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NBS TECHNICAL NOTE

491

# Gravity Measurements And the Standards Laboratory

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards

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# NBS TECHNICAL NOTE 491

ISSUED AUGUST 1969
Nat. Bur. Stand. (U.S.), Tech. Note 491, 10 pages (Aug. 1969)
CODEN: NBTNA

# Gravity Measurements and the Standards Laboratory

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# GRAVITY MEASUREMENTS AND THE STANDARDS LABORATORY

D. R. Tate

The local value of the acceleration due to gravity is a fundamental datum for almost every standards laboratory as it, together with accurate standards of mass, is the basis for the standards involving force. Instruments used as standards in this area include precise deadweight piston gages, deadweight calibrators for force transducers, liquid manometers, and earth field accelerometer calibrators. The practical realization of the absolute ampere and the absolute volt require a knowledge of force. This paper presents the basic information about how gravity measurements are made and outlines procedures for obtaining a suitable value for a given location. It also gives a brief discussion of the background and meaning of the term "standard gravity", and its application in the computation of forces in units of the pound-force and the kilogram-force.

Key words: Absolute gravity, deadweight, force, geodetic pendulum, gravity, gravity meter, Potsdam system, standard gravity, units of force.

## 1. Introduction

The local value of the acceleration due to gravity is a matter of considerable importance to almost every standards laboratory as it, together with accurate standards of mass, is the basis of all force measurements. Instruments for the measurement of acceleration, accelerometers, have also reached a stage where, for earth field calibrations, the acceleration due to gravity must be known quite accurately. It is the purpose of this paper to present the basic information about how gravity measurements are made and to outline the procedures for obtaining a suitable value for a given location.

## 2. Gravity Networks

Gravity measurements have been made by geodesists for many years and a well developed science, with instrumentation and technique, has grown up in the field. Primarily the interest of the geodesist is to gain a better knowledge of the shape and structure of the earth, and the work that has been done has resulted in a network of gravity values

covering the greater portion of the habitable parts of the world. This network, with its excellent coverage in Europe and the Americas, affords a ready-made basis for obtaining satisfactory values in most laboratories.

It is helpful to understand the methods by which gravity networks have been established. The direct measurement of the acceleration due to gravity through the observation of time and distance is a difficult undertaking and not well adapted to survey methods. Consequently the principle has been to establish an absolute value at some one point and to make the survey measurements with instruments that measure the difference in gravity between two points, starting at the absolute site and moving out in the closed-loop technique commonly employed in other types of surveys. The network values in existence today are derived from an absolute measurement made in Potsdam, Germany.

## 3. Absolute Measurements

Absolute determinations of the acceleration due to gravity, in addition to being difficult and time consuming, have in the past been subject to serious systematic errors which were large when compared to the accuracy of differential measurements made with survey type instruments. Consequently it has been desirable to make additional absolute measurements at various points in the world network, even though only one such determination is theoretically necessary. Up to quite recently, absolute measurements were restricted by practical considerations to locations in the national standards laboratories of some of the larger nations.

The classic absolute measurement was made at Potsdam by Kühnen and Furtwängler and published in 1906[1]*. It was made by the use of reversible pendulums of the Kater type and resulted in a value of 9.81274 m/s$^2$ for that station. Subsequent absolute determinations made in Washington by Heyl and Cook[2] and at Teddington, England by Clark[3], gave values 15 to 20 parts per million less than the Potsdam result after consideration of the gravity differences between the sites. In recent times absolute measurements have been made from observations on freely falling objects in vacuum by several workers[4,5,6,7,8,9]. A discussion of absolute determinations is given by A. H. Cook[10].

The conclusion has been reached that the original Potsdam value is in error by about 14 parts per million, and in October of 1968 the International Committee on Weights and Measures adopted a resolution that, for the needs of metrology, the value at Potsdam should be regarded as 9.81260 m/s$^2$.

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*Figures in brackets refer to references at the end of this paper.

Currently the development of stabilized gas laser systems has made it possible to make absolute determinations in which the falling object is one reflector of a Michelson interferometer. This technique improves the accuracy over the older methods by about an order of magnitude. Measurements by this method are under way by Faller[11] and Sakuma[12]. Faller's apparatus is sufficiently portable that it can be transported from one laboratory to another and it is expected to prove most useful in giving precise values for a number of points in the pattern of the world gravity network.

## 4. Survey Measurements

As indicated previously, the values of gravity at most points of interest are determined from the cumulated differences between a series of stations starting at a point where the absolute value is known or assumed. Usually, values for well known intermediate points have been established through a number of redundant measurements made over a period of years. An interesting example of this is the well established gravity tie made between Potsdam and Bad Harzburg. Since Potsdam lies in East Germany, it was not accessable to geodesists from nations outside of the Soviet Bloc for many years and Bad Harzburg in Western Germany became the reference point for the western nations.

Instruments used for gravity surveys fall into two basic categories. Originally, all such measurements were made with instruments of the pendulum type, known as geodetic pendulums. These pendulums have, in essence, an unknown but constant length, and the difference in gravity between two stations is deduced from the changes in period of the pendulum when it is swung at the two sites. Successful measurements with pendulums of this type require highly developed techniques, painstaking care, and considerable time for each determination[13].

In more recent years, a different type of instrument has been used for gravity survey work. These instruments, known as gravity meters, operate on the principle that a mass suspended by a spring will change its equilibrium position with changes in gravity. Since gravity differences are small, such instruments are examples of ingenious design[14] and construction. Usually the mass is attached to an arm pivoted at the other end with the torque due to the mass being opposed by a non-linear spring and moment arm arrangement. The arrangement is usually such that the system is very near to unstable equilibrium so that a small change in the force on the mass tends to produce a large displacement of the arm. The actual motion is limited by stops and the arm is brought back to its initial position by a fine spring actuated by a micrometer screw adjustment. These instruments must be calibrated by measuring gravity differences between points having known differences, such as stations with geodetic pendulum gravity values.

## 5. Local Values of Gravity

The principal agency of the United States Government for the determination of gravity values is the Coast and Geodetic Survey, a part of the Environmental Science Services Administration of the U. S. Department of Commerce. The Coast and Geodetic Survey has on file values of gravity measured in many parts of the country and new measurements are constantly being added to the list.

In cases where a standards laboratory is working at an exceptionally high level of accuracy, it may be desirable to have a direct gravity tie made by means of a gravity meter from the nearest network site to the point of interest in the laboratory. For many laboratories, a value of ample accuracy can be obtained by computation from the nearest established network station. The Coast and Geodetic Survey can provide assistance with such a computation if they are given the latitude, longitude, and elevation of the laboratory point where the value is needed. The latitude and longitude should be furnished to the nearest 0.1 minute of arc, and the elevation above sea level within about five feet. At most locations of standards laboratories, this type of information will enable the computation of gravity with a standard error not exceeding $\pm$ 0.00004 $m/s^2$. Values furnished by the Coast and Geodetic Survey are accompanied by an estimate of standard error.

In general, repeat gravity measurements for a particular location are unnecessary. Diurnal variations, following the luni-solar tidal cycle, do not exceed $\pm$0.000003 $m/s^2$, and secular changes of the order of 0.00001 $m/s^2$ have not been confirmed since the advent of precise gravity measurements.

## 6. Standard Gravity

The term "standard gravity" is so widely encountered and so much misunderstood that some explanation is desirable. Standard gravity bears no relationship to any system of gravity measurements, absolute or otherwise. It is simply an acceleration that has been adopted by agreement among the nations of the world as the definition of the engineering units of force. These units of force, taken as the weight of a unit mass, were objectionable in their original form because they varied with the location of the mass on the surface of the earth. By common consent it was agreed that such a definition must be tied to some specific location on the globe, and a value at 45 degrees latitude and sea level seemed a reasonable compromise. Any other location would have been equally valid providing everyone agreed to it. In 1901, five years before the publication of the Potsdam absolute determination, the International Conference on Weights and Measures adopted a value of 9.80665 $m/s^2$ as the definitive value[15]. This value had been obtained by reducing an absolute measurement made at the International Bureau of Weights and Measures by Monsieur Defforges to 45 degrees and sea level. Later it was pointed out that, because of the existence of

gravitational anomalies, there was no unique value for that latitude and elevation. In 1913, the International Conference reviewed the situation and reaffirmed that the conventional value should be represented by the number 9.80665 $m/s^2$. In essence, this meant that the definition of the practical units of force was not to be based on the weight at 45 degrees and sea level, but on the arbitrarily adopted acceleration value.

It may be seen from this that the value of 9.80665 $m/s^2$ is an arbitrary value of acceleration and not the value of gravity at a specific location. It is not expected that this value will be changed in the future.

## 7. The Computation of Forces

In the standards laboratory it is frequently necessary to calculate the force exerted by a given mass in air as, for example, in the operation of a deadweight piston gage pressure standard. The force, F, is calculated from the relationship

$$F = Kmg\left(1 - \frac{\alpha}{\rho}\right)$$

where $m$ is the mass, $g$ is the local value of the acceleration due to gravity, $\alpha$ is the density of air, and $\rho$ is the density of the mass. If $m$ is given in terms of "apparent mass versus brass standards in normal air", $\alpha$ should be assigned the value 1.2 $kg/m^3$, the adopted value for the density of normal air, and $\rho$ should be assigned the value 8400 $kg/m^3$, the adopted value for the density of brass.

The quantity $K$ is a numerical factor, the value of which depends upon the units of F, m, and g. In the SI system of units,

$K = 1$, for $F$ in newtons, $m$ in kilograms, and $g$ in meters per second squared.

Other relationships are as follows:

$K = 1$, for $F$ in dynes, $m$ in grams, and $g$ in centimeters per second squared,

$K = 1$, for $F$ in poundals, $m$ in pounds mass, and $g$ in feet per second squared,

$K = 1/32.17405$ for $F$ in pounds force, $m$ in pounds mass, and $g$ in feet per second squared,

$K = 1/980.665$ for $F$ in pounds force, $m$ in pounds mass, and $g$ in centimeters per second squared,

$K = 1/9.80665$ for $F$ in kilograms force (kiloponds), $m$ in kilograms mass, and $g$ in meters per second squared.

## 8. Summary

Most laboratories that carry out calibration functions involving force measurements, such as various forms of pressure measuring instruments, force transducers, and certain types of accelerometer calibrations using the earth's field as a reference, need a suitable value of gravity established within the laboratory. The value need not be determined by actual gravity measurement except in exceptional cases. A value within 0.0001 $m/s^2$ (10 milligals) gives force values within one part in 100,000 which is adequate for most purposes. For most locations of standards laboratories, a value well within this limit can be obtained from the Coast and Geodetic Survey. In any case, it is advisable to write to them to ascertain if it is available.

The term "standard gravity", e.g. 9.80665 $m/s^2$, is in reality an arbitrarily defined acceleration adopted to define units such as the pound-force and kilogram-force. It is not the value of gravity at any specific location and is not affected by any corrections to the Potsdam system.

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